10-ps timing with 3D-trench silicon pixels at extreme rates

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TimeSPOT — TIME and SPace real-time Operating Tracker

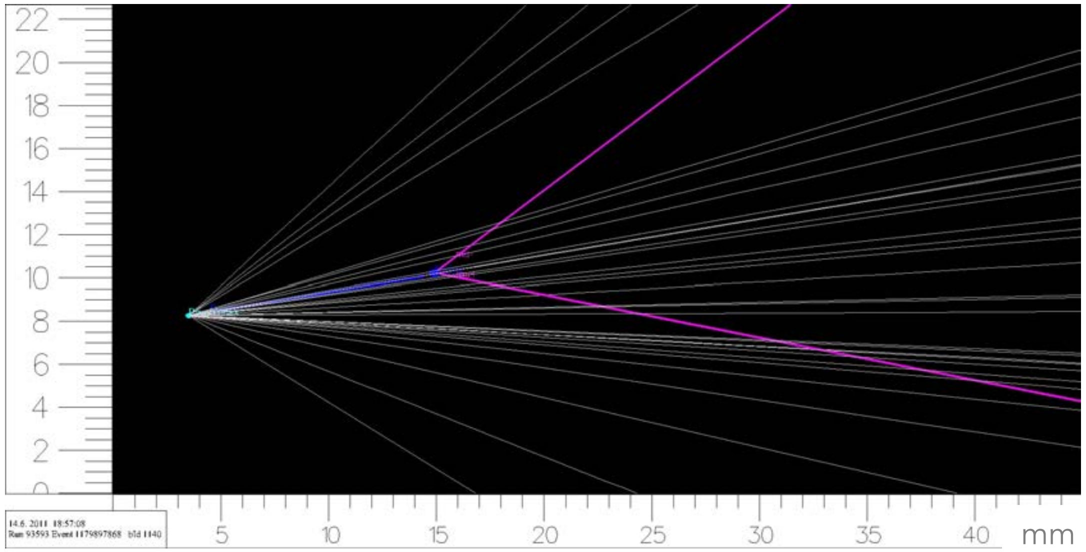
INFN — Istituto Nazionale di Fisica Nucleare

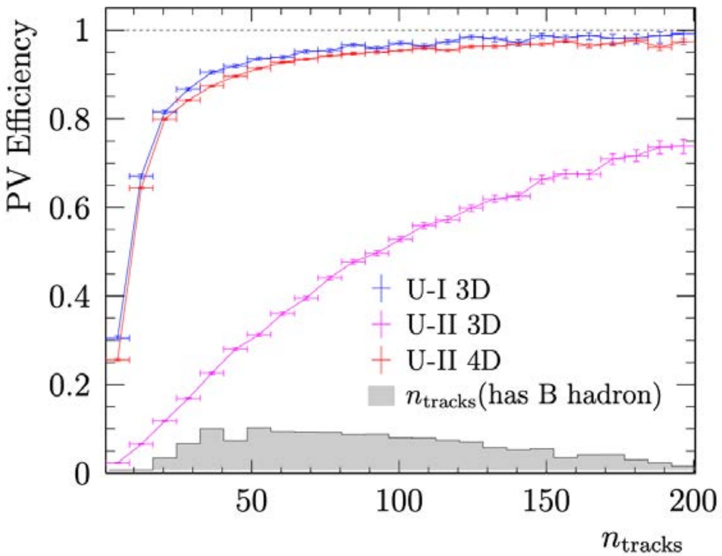
4D trackers/pixels: high density timing pixels

(beyond pile-up mitigation: when timing layers are not enough)

Plots from:
Considerations for the VELO detector at the LHCb Upgrade II – CERN-LHCb-2022-001

B_{0s} meson decaying into a μ^+ and μ^- pair





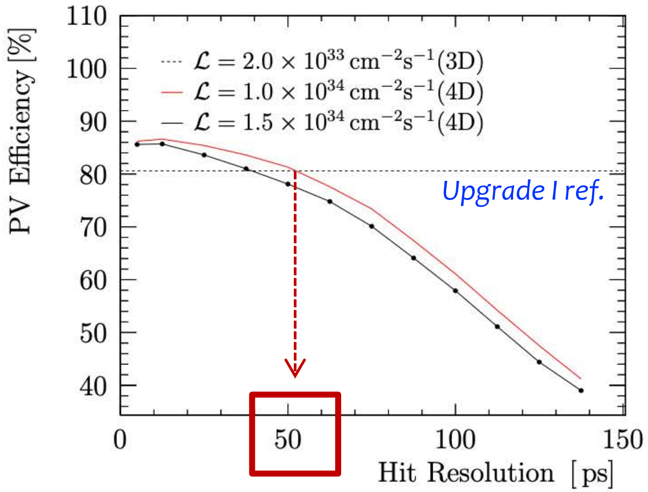
Reconstruction efficiency vs the number of tracks per primary vertex, comparing the Upgrade I 3D reconstruction in both data conditions, and a variant using timing information to resolve the primary vertices

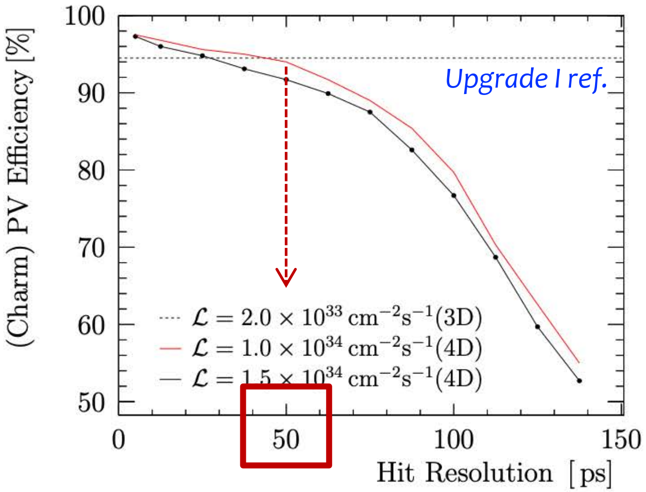
4D pixel:
A solid state pixel sensor (pitch ≈ 50 μm) bearing time information

Track merging: bad Primary (and Secondary) Vertex reconstruction

Incorrect PV assigned to tracks: poorly measured lifetime (dominant sistematic effect for time-dependent analysis)

PV reconstruction efficiency as as function of the single hit resolution, for all vertices (left) and for vertices where at least one of the decay products is a charm hadron (right).





50 ps per hit (corresponding to 20 ps per track) are sufficient to recover the Upgrade-I efficiency

Crucial requirements for 4D-Tracking

A necessary technique for Physics at high intensity, in the **next generation of upgrades** in experiments at colliders: **LHCb Upgrade-II** (run5), **HIKE** (NA62 Upgrade), **CMS-PPS** (run4), **ATLAS AFP** (run5?), **ν–tagging**, **Pioneer** (proposal at PSI, π rare decays), **CMS endcap** (run5)… FCC–hh (far perspective)

1. **Space Resolution $\sigma_s \approx 10$ μm**
2. **Time Resolution $\sigma_t \leq 50$ ps per hit**
3. **Radiation hardness to high fluences $\Phi = 10^{16} \div 10^{17}$ 1 MeV n_{eq}/cm^2**
4. **Detection efficiency ε > 99% per layer tipically required (high fill factor)**
5. **Material budget must be kept below 1 ÷ 0.5 % radiation length per layer**

Fast and rad-hard sensors

Key requirements for read-out electronics:

1. **Pixel pitch ≈ 50 μm (unless amplitude information for CoG techniques is used)**
2. **Time Resolution $\sigma_t \leq 50$ ps on the full chain ($\sigma_t = \sigma_{sensor} \oplus \sigma_{FE} \oplus \sigma_{TDC}$)**
3. **Radiation hardness TID > 1 Grad**
4. **Power budget per pixel ≈ 25 μW (referred to 55 μm pitch, 1.5 W/cm²)**
5. **Data BW ≈ 100 Gbps/cm²**

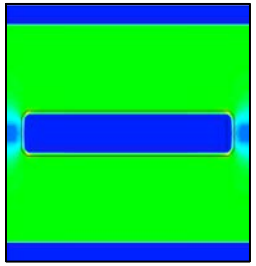
CMOS 28-nm electronics

Sensor fabrication @ FBK

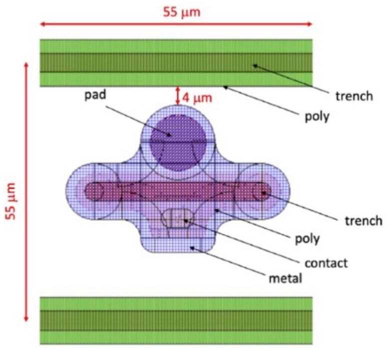
2 batches (2019 and 2020)

The optimal geometry

- 3D-trench
- 5 x 40 x 135 µm³ trench
- 150 µm pixel depth



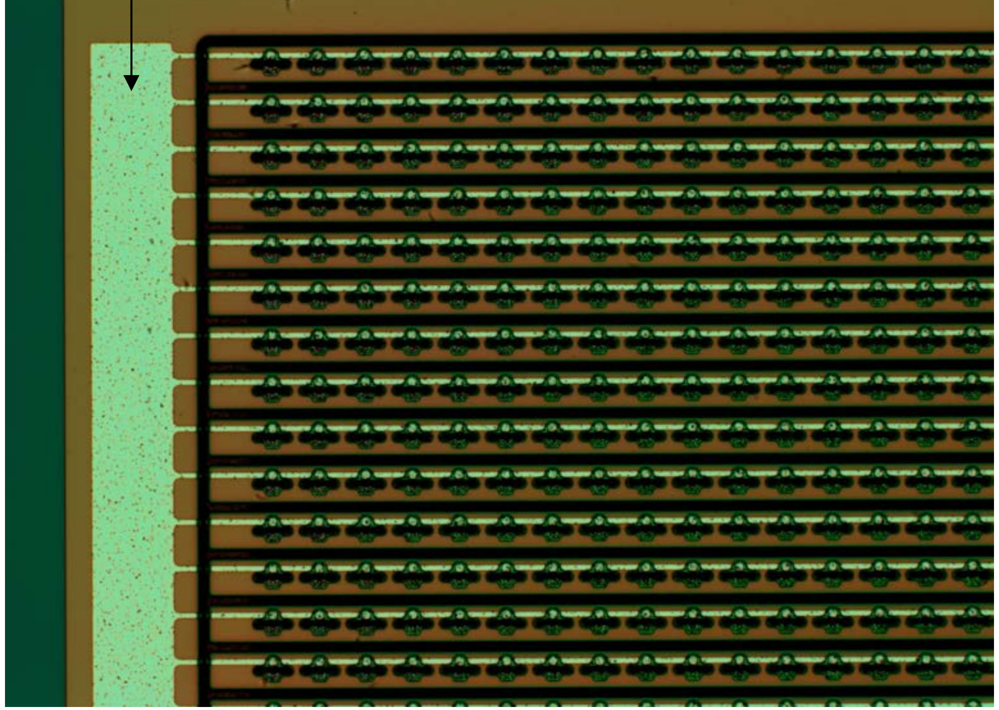
Pixel geometry



Pixel layout

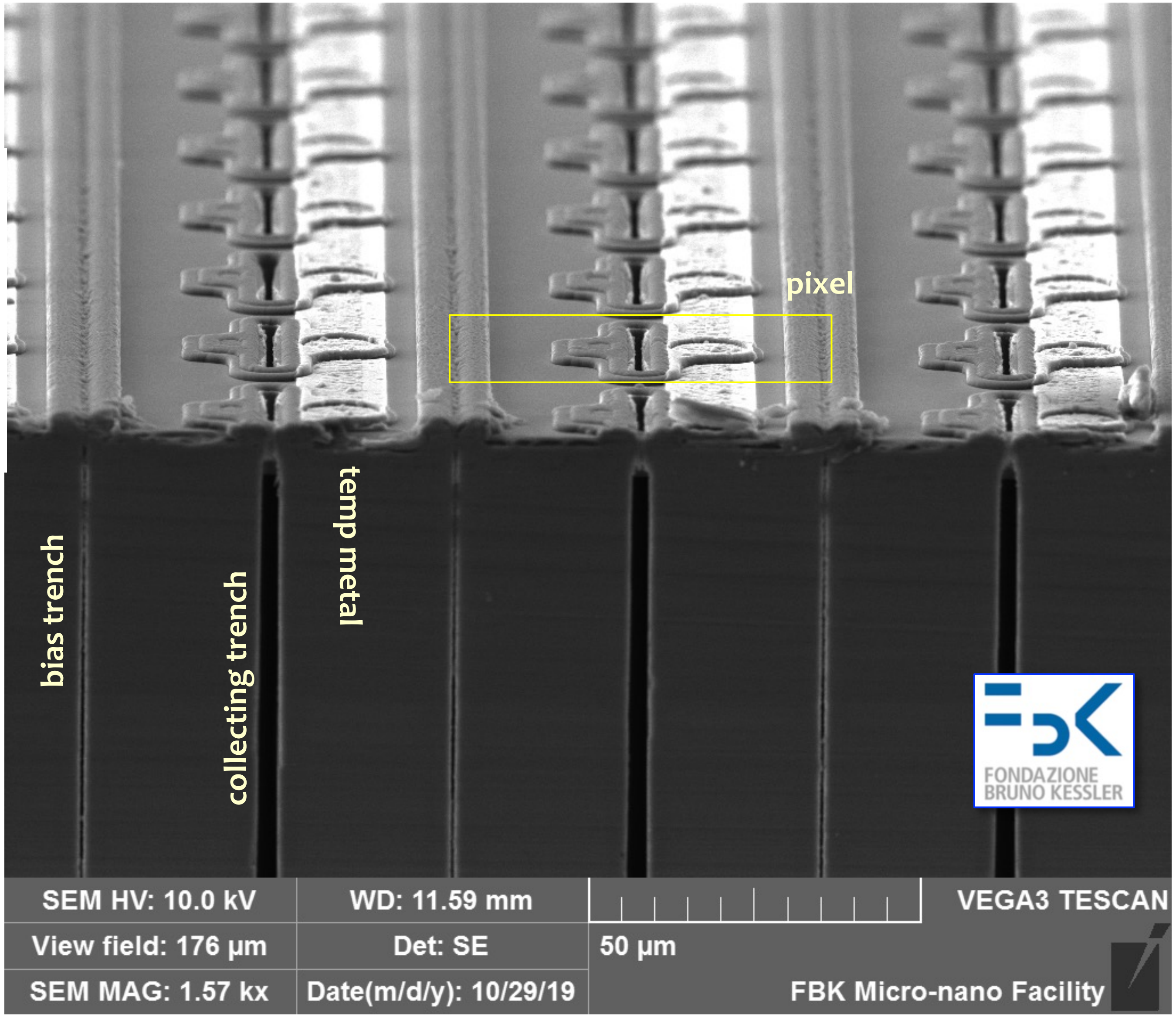
temp metal for static tests

Matrix of 3D-trench sensors



collecting trench

bias trench



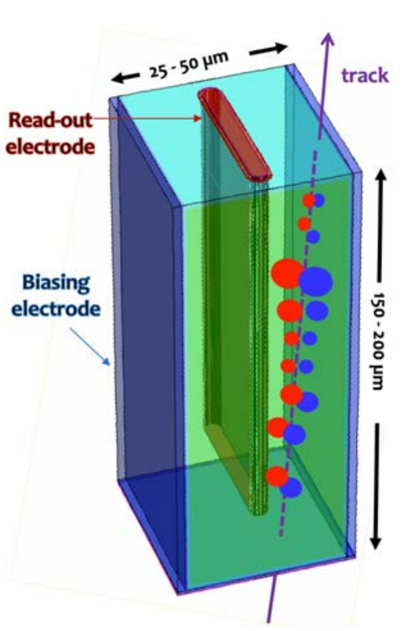
Deep Reactive Ion Etching

Bosch technology

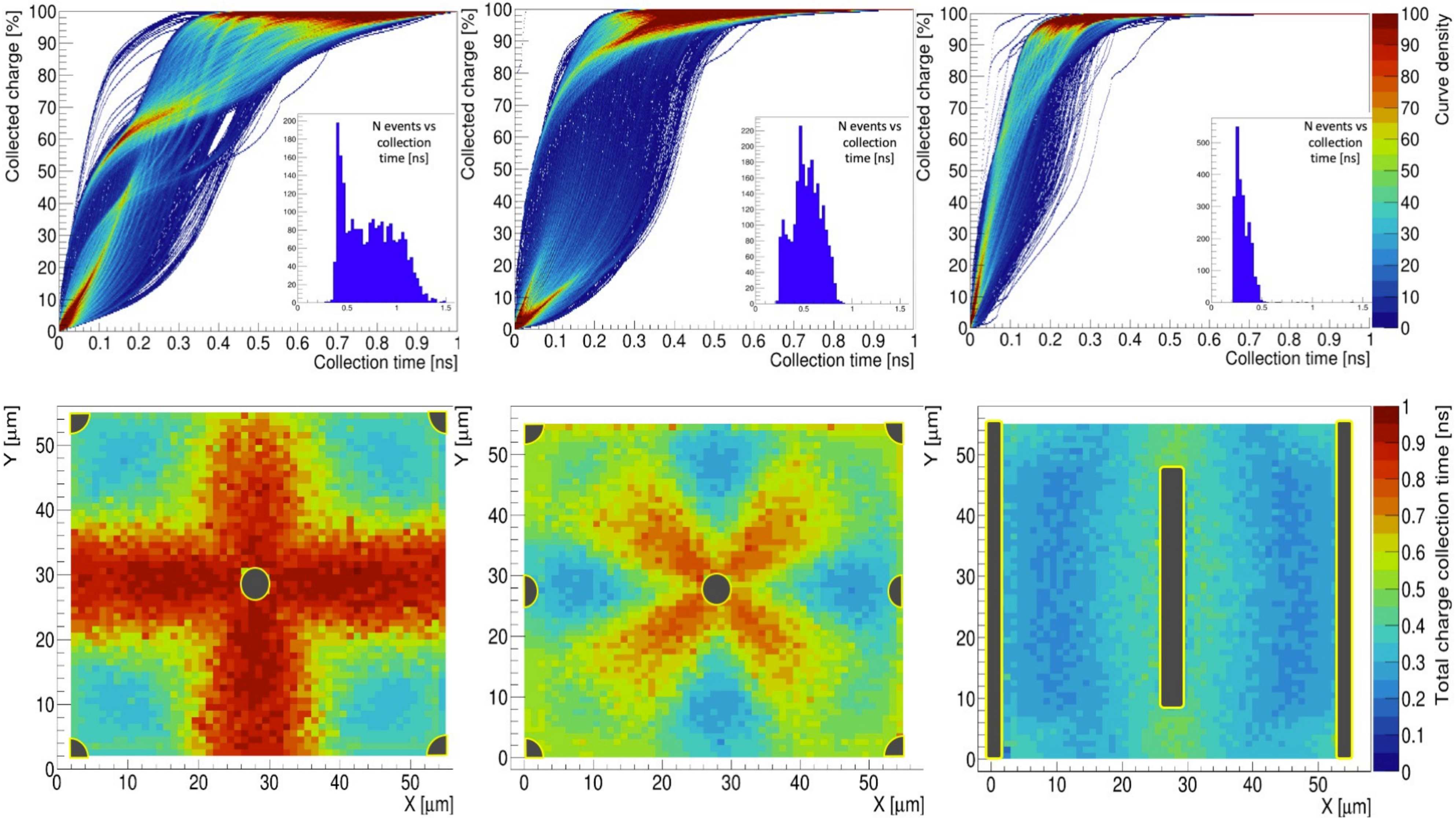
(developed for MicroElectroMechanicalSystem technology)

Charge Collection Time in 3D sensors

Curves and maps



A "geometric sensor"



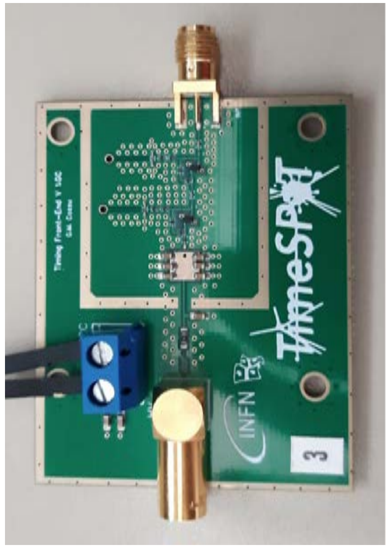
Time performance comparison among three different 3D geometries at V_{bias} = –100V. (Top) percentage of total charge collected on the electrodes versus time. (Top inserts) distribution of charge collection time for the three geometries. (Bottom) time for complete charge collection versus impact point for the same geometries. Each simulation is based on about 3 000 MIP tracks.

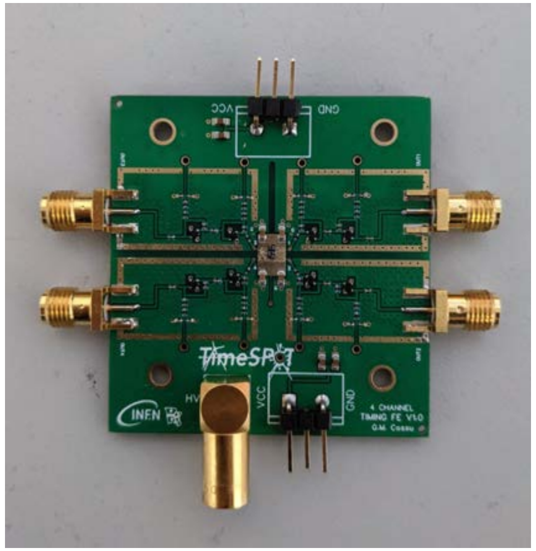
Latest results

Test-beams Nov21 & May-June 22 @SPS/H8

New faster dedicated front-end electronics

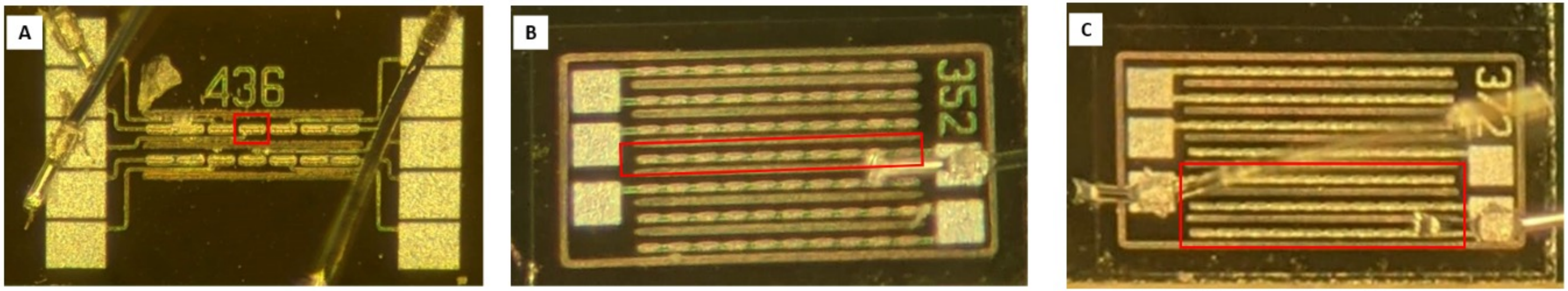
Si-Ge input stages
$t_r \approx 100$ ps.
Measured *jitter*
< 7ps @ 2 fC
Power ≈ 70 mW/channel





1. Not-irradiated:
   - Landau distributions vs V_{bias}
   - Time resolution
   - Geometrical efficiency vs tilt angle
   - Time resolution vs tilt angle
2. Same with samples irradiated @ Φ = 2.5 10^{16} 1-MeV-n/cm^2
3. First studies on charge sharing

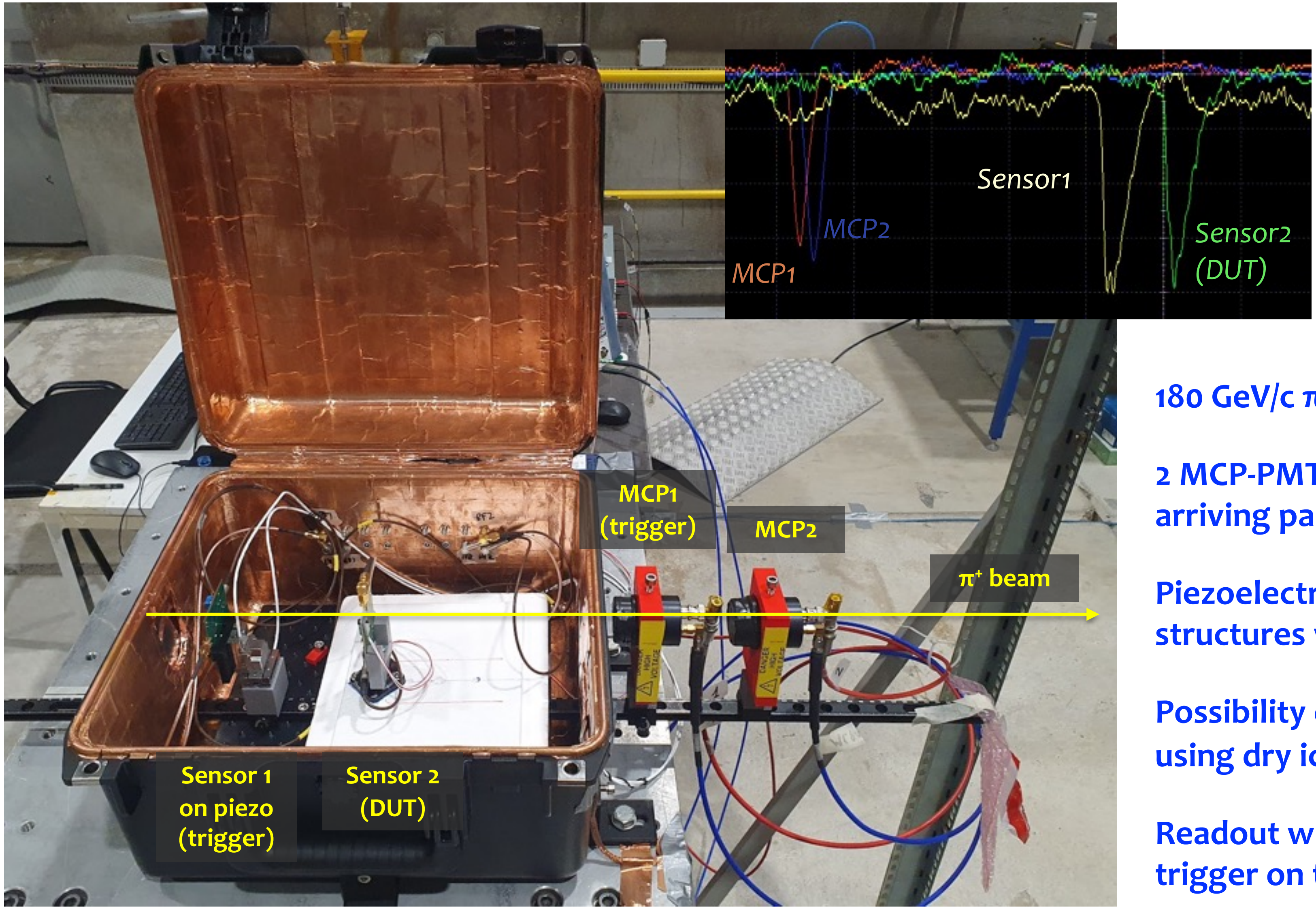
Tested structures. For each sensor the active area is shown in red.
(A) Single pixels sensor; (B) strip sensor; (C) triple strip sensor



See also: "Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels" (submitted to Frontiers in Physics)

Experimental setup

Test-beams Nov21 & May22 @SPS/H8



180 GeV/c π^+ beam

2 MCP-PMTs on the beam line to time-stamp the arriving particle (σ_{avg} = 5 ps)

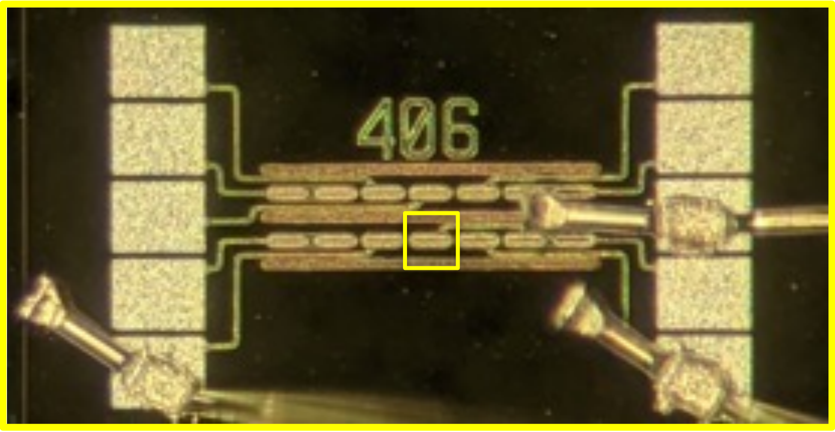
Piezoelectric stages to precisely align the two 3D structures with beam, all mounted in a RF-shielded box

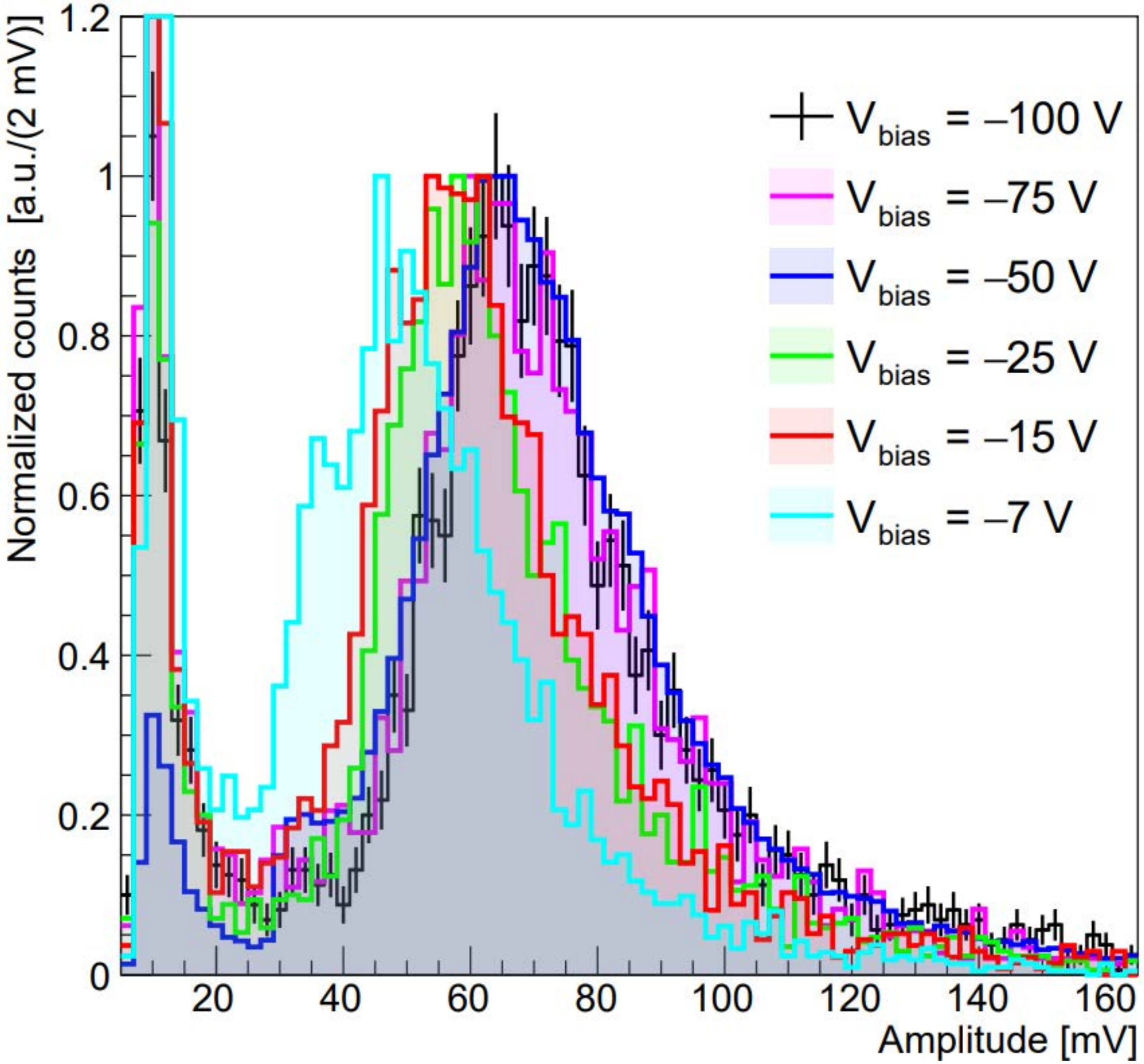
Possibility of operating the fixed sensor down to -40°C using dry ice to test irradiated sensors

Readout with an 8 GHz bandwidth 20 GSa/s scope: trigger on the AND of one 3D sensor and one MCP-PMT

Amplitude distributions vs bias

Single pixel, not irradiated





Normal pion incidence (α_{tilt} = 0°)

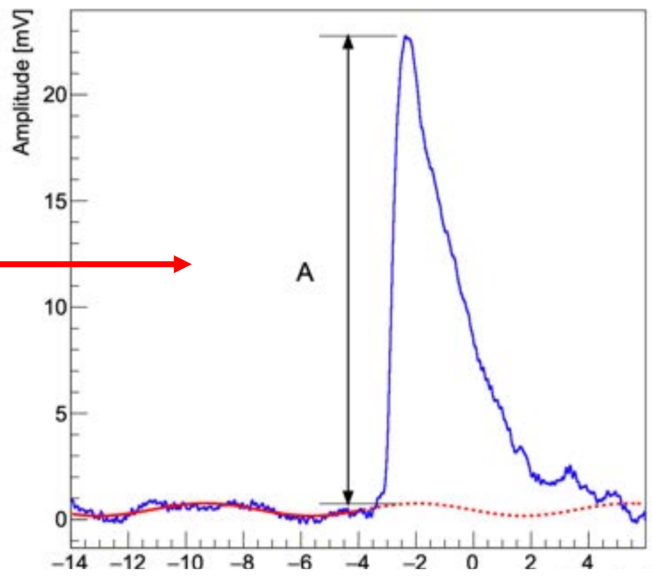
DUT not on the trigger

Very good sensor performance even at **low V_{bias}** (prompt full depletion)

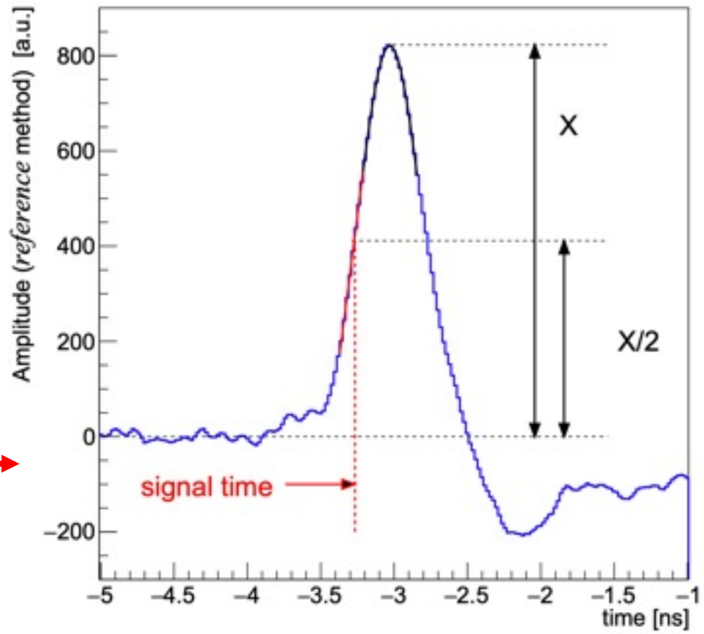
Waveform processing for time resolution analysis

For each sensor's waveform:

- Signal baseline (red-dashed line) is evaluated on an event-by-event basis
- The signal amplitude **A** is measured w.r.t. to the event baseline



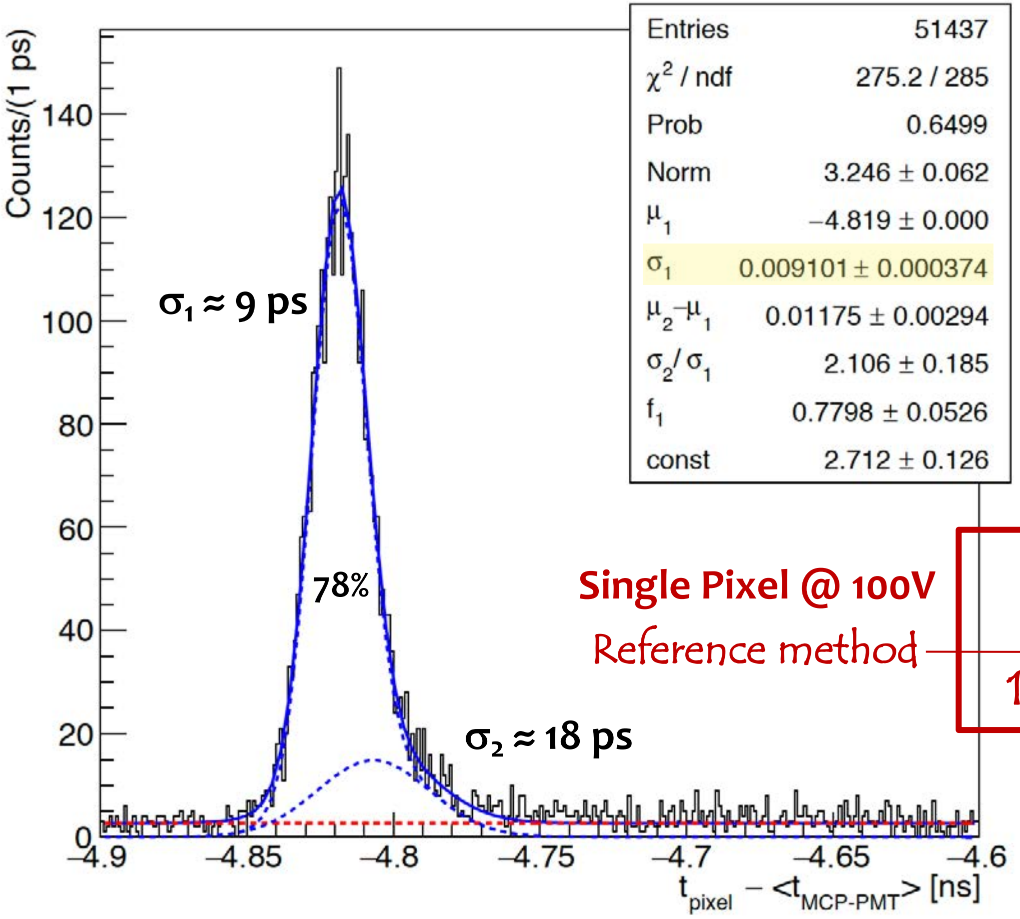
- **Signal time of arrival evaluated with various methods:**
  - **Leading-edge:** time at 15 mV signal amplitude, linear interpolation around threshold (time-walk effect is present)
  - **LE corrected for the amplitude** to suppress the time-walk effect
  - **Spline:** a classic CFD at 20% with rising edge interpolated with a spline
  - ***Reference (CFD/ARC*)* :** subtract each waveform from a delayed (by about half of the signal rise time) copy of itself, then, on the resulting signal, **trigger at x/2 height**



*Amplitude and Rise-time Compensation method

Timing measurements
(single pixel @ α_{tilt} = 0°, not irrad.)

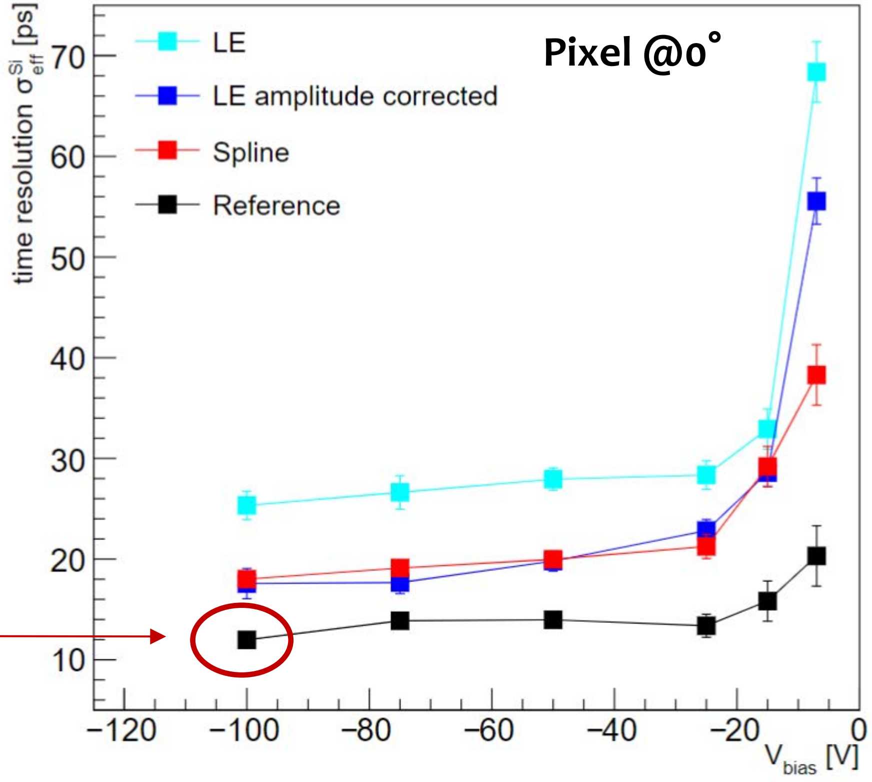
LE: Leading edge, NO ToT correction
LE: Leading edge, ToT correction
Spline: Classic CFD
Reference: ARC/CFD method



Distribution of the difference between the TOA of the single pixel and the time reference, $t_{pixel} - \langle t_{MCP-PMT} \rangle$, for the single pixel perpendicular to the beam at V_{bias} = −100 V with the reference method. The distribution is fit with the sum of two Gaussian functions (blue dashed lines) describing the signal, and a constant (red dashed line) modelling the background.

Single Pixel @ 100V
Reference method

σ_t^{eff}
11.5 ps



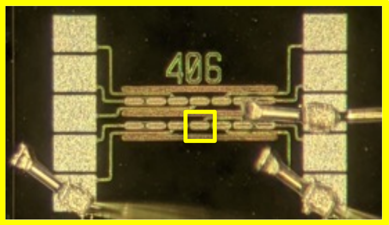
$$(\sigma_t^{eff})^2 = f_1(\sigma_1^2 + \mu_1^2) + (1 - f_1)\cdot(\sigma_2^2 + \mu_2^2) - \mu^2$$

Where f_1 is the fraction of the core Gaussian and μ is defined as

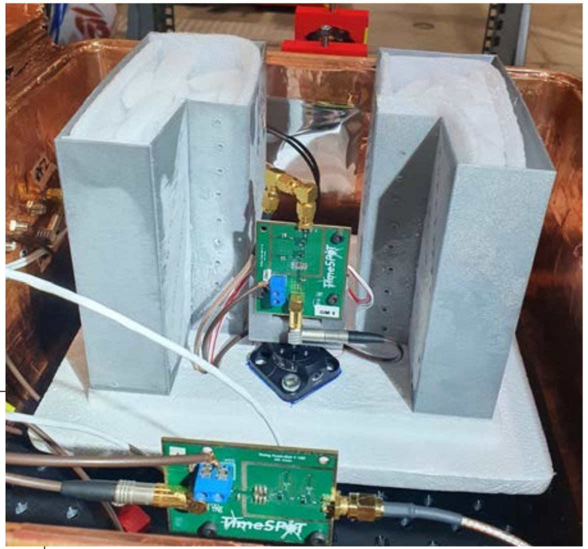
$$\mu = f_1\mu_1 + (1 - f_1)\cdot\mu_2$$

σ_t^{eff} **takes into account the two-Gaussian behaviour**

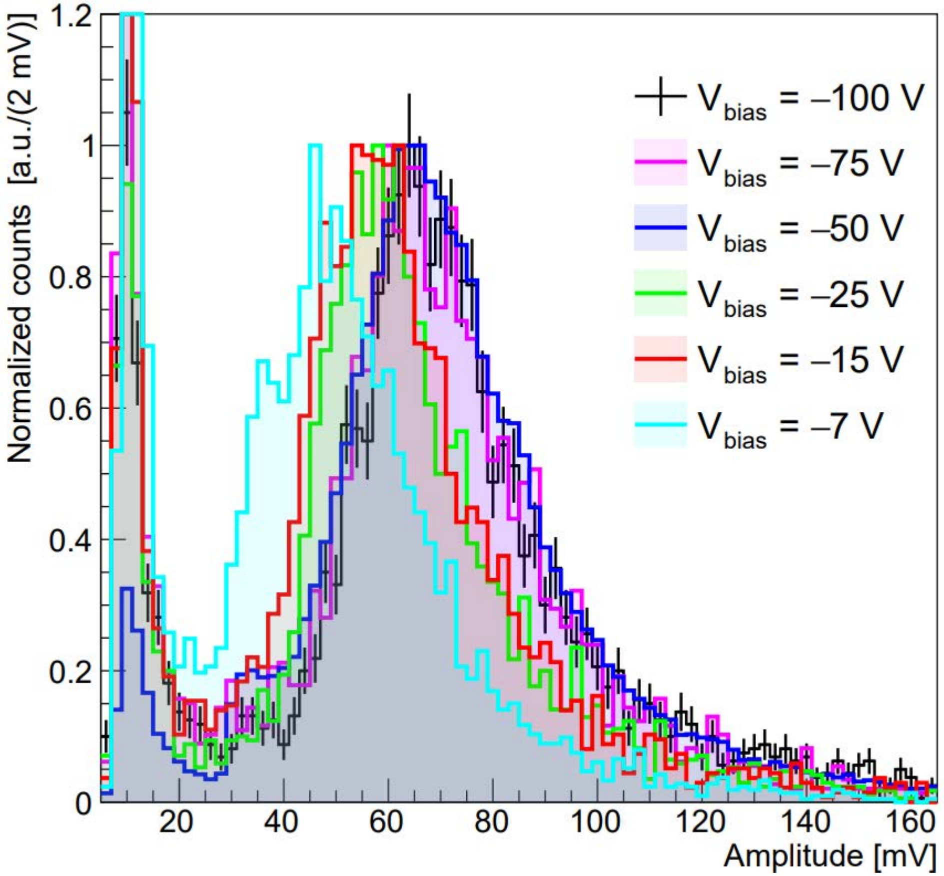
Details on the paper: "Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels" **submitted to Frontiers in Physics**



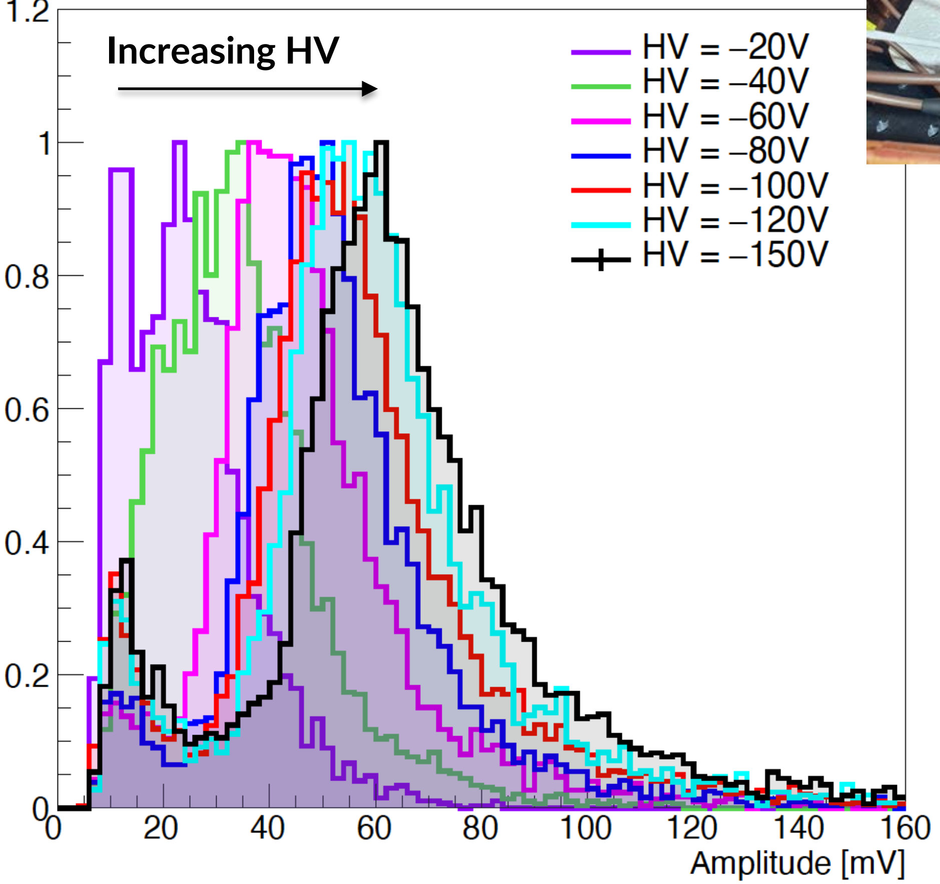
Amplitude distributions vs bias
Single pixel, ***irradiated***



Not IRRADIATED, α_{tilt} = 0°

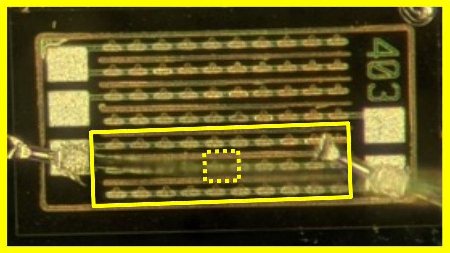


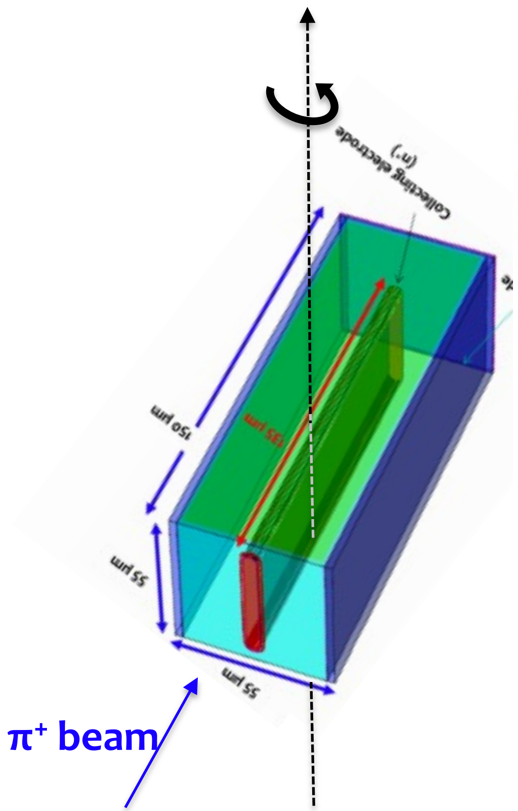
Irradiated @ 2.5 10^{16} n_{eq}/cm^2 , α_{tilt} = 0°

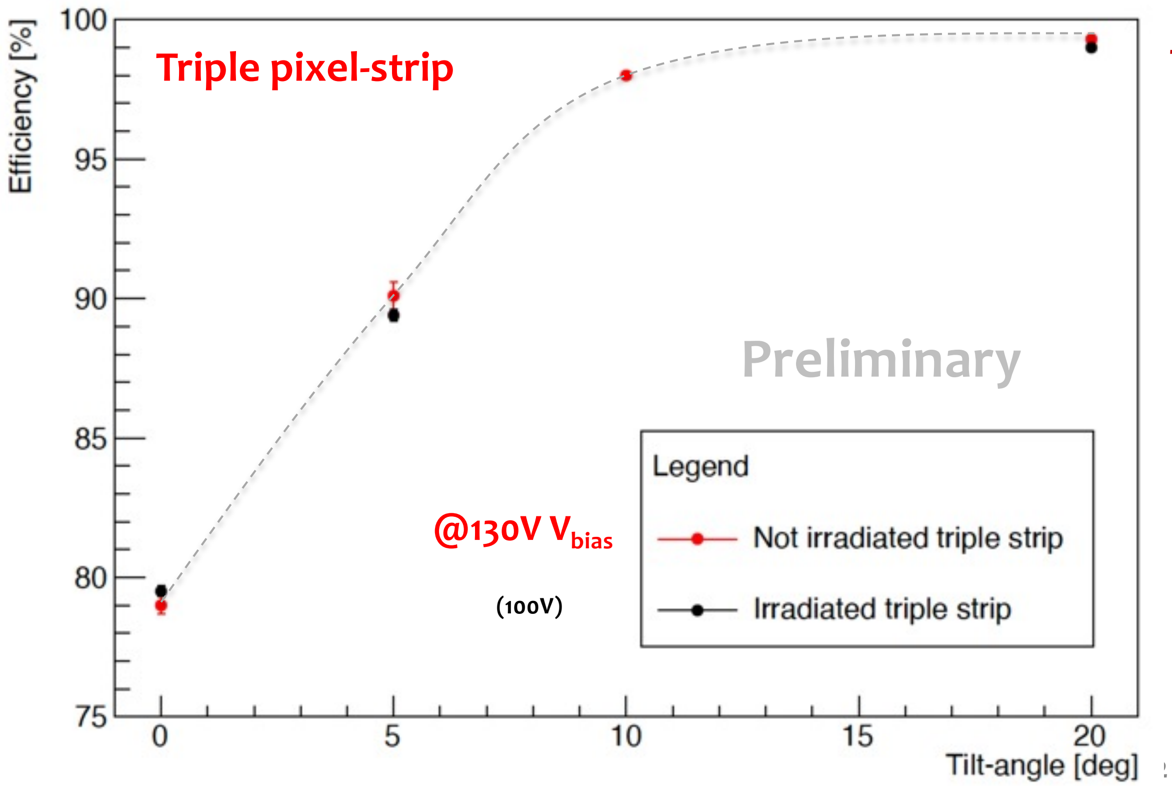


The effect of fluence is evident from the ΔV_{bias} needed to reach the same Amplitude

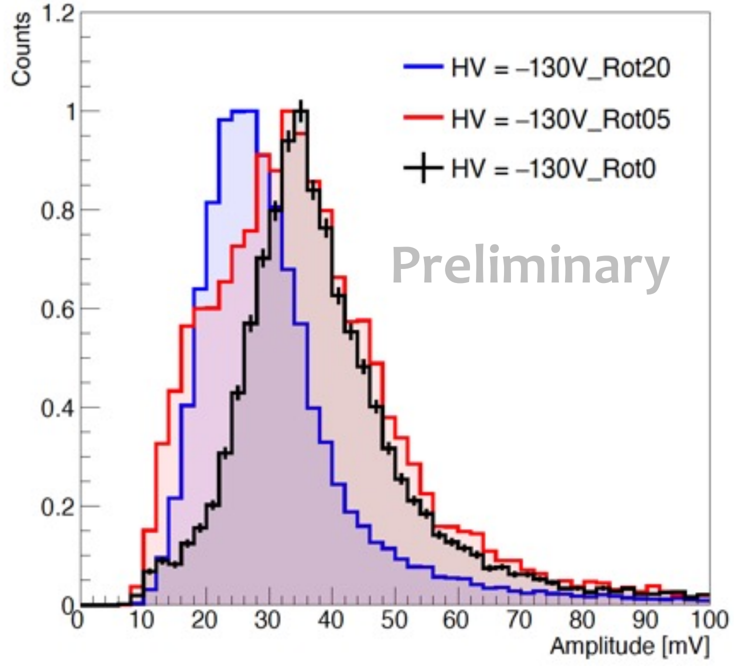
Irradiated/not irradiated sensors: geometrical efficiency







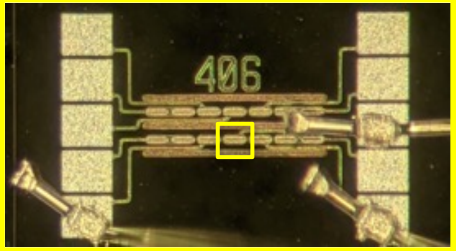
Triple strip @ 2.5 10^{16} n_{eq}/cm^2 , α_{tilt} = 0°, 5°, 20°



The inefficiency (at normal incidence) due to the dead-area of the trenches is fully recovered by tilting the sensors around the trench axis

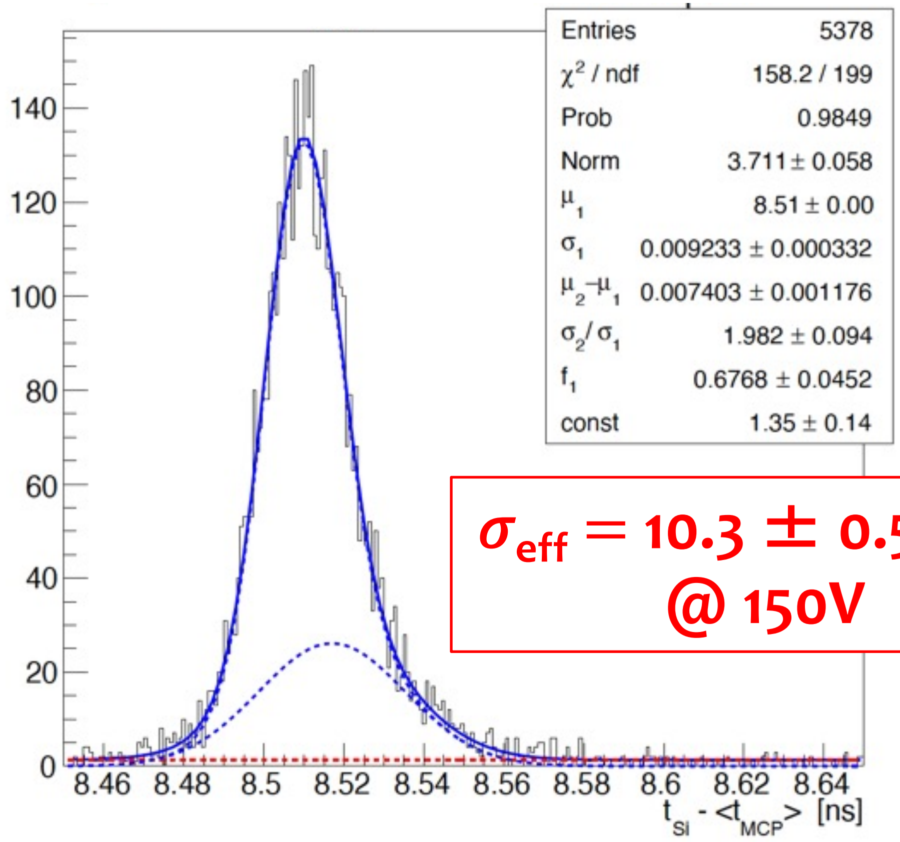
also for sensors irradiated with fluences of $2.5 \cdot 10^{16}$ 1-MeV neutron equivalent

Irradiated sensors: timing performance

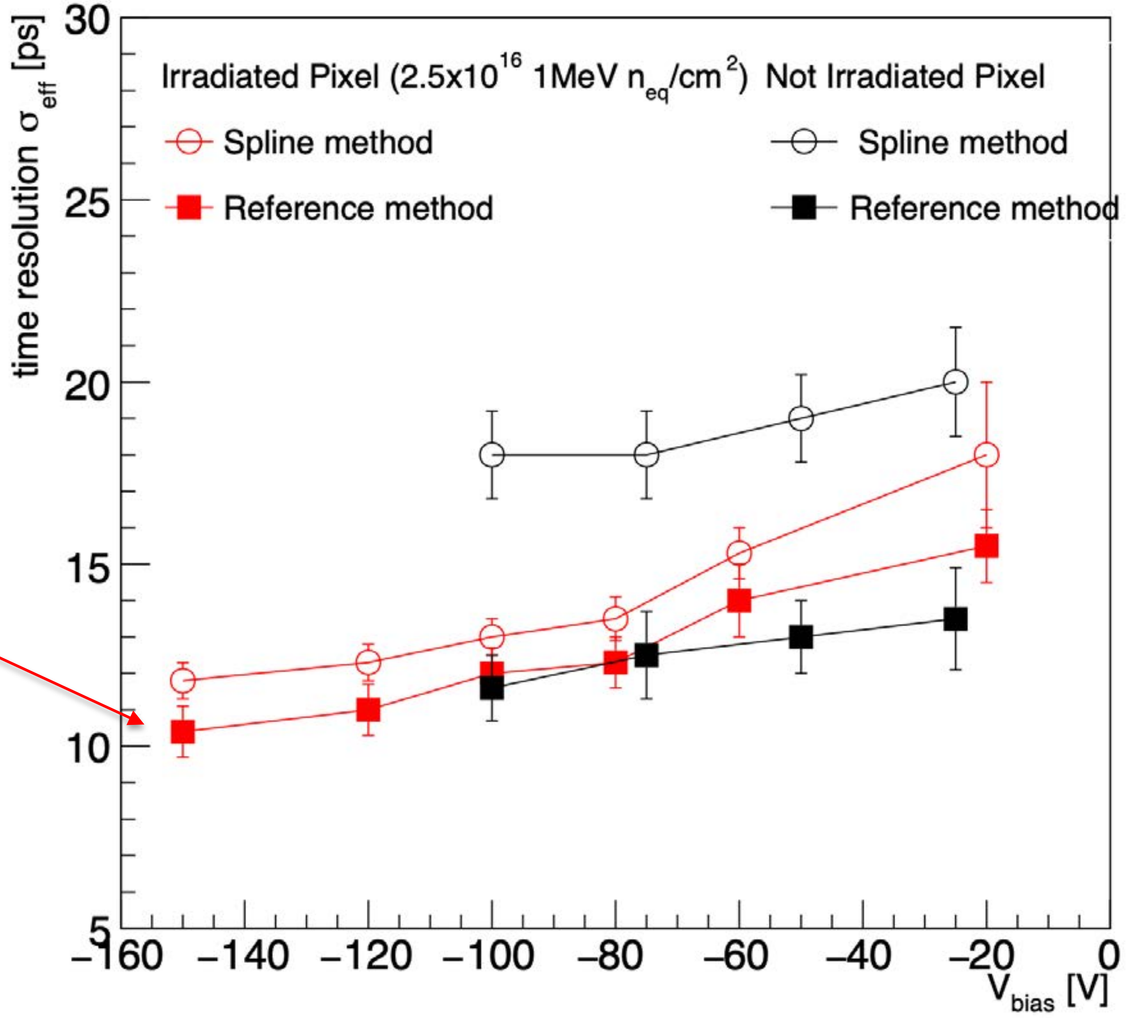


Irradiated @ 2.5 10^{16} n_{eq}/cm^2 , α_{tilt} = 0°

$\sigma_1 \approx 9$ ps
$\sigma_2 \approx 18$ ps



$\sigma_{eff} = 10.3 \pm 0.5$ ps
@ 150V

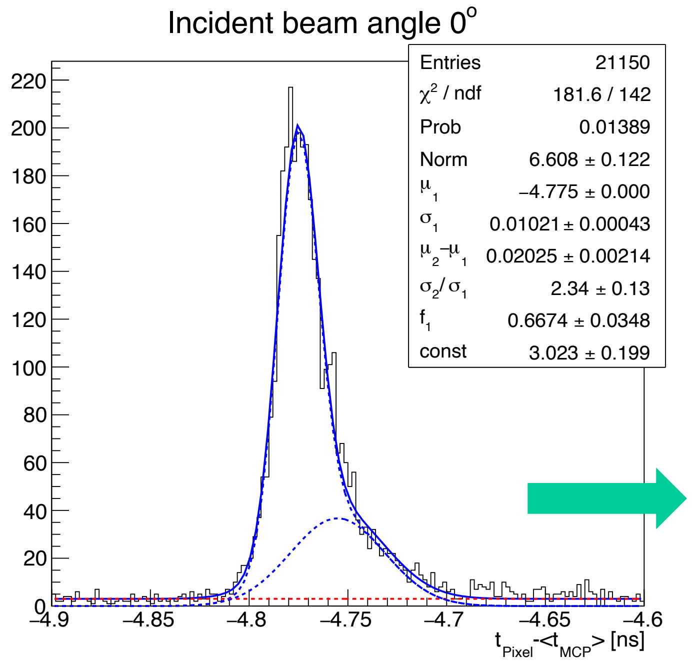


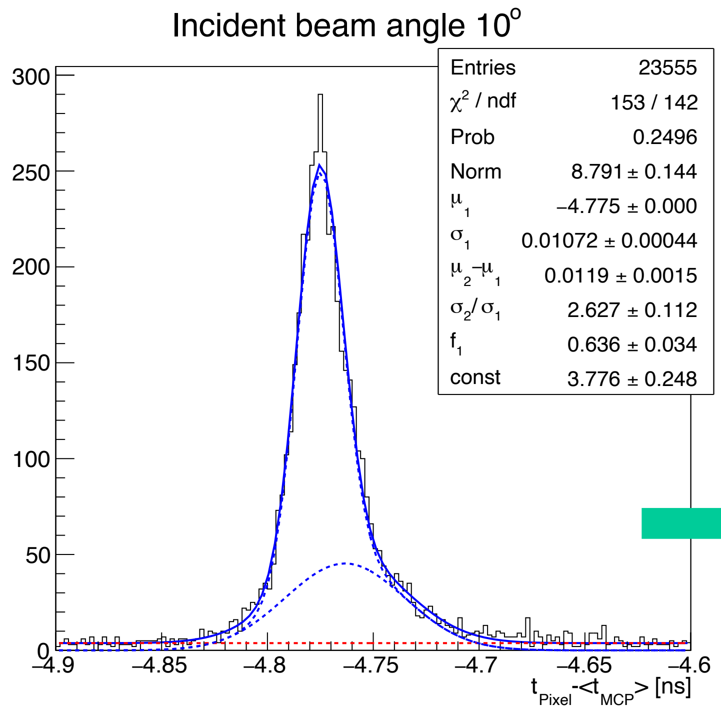
To be compared with 11 ps @ 100 V of the not-irradiated case

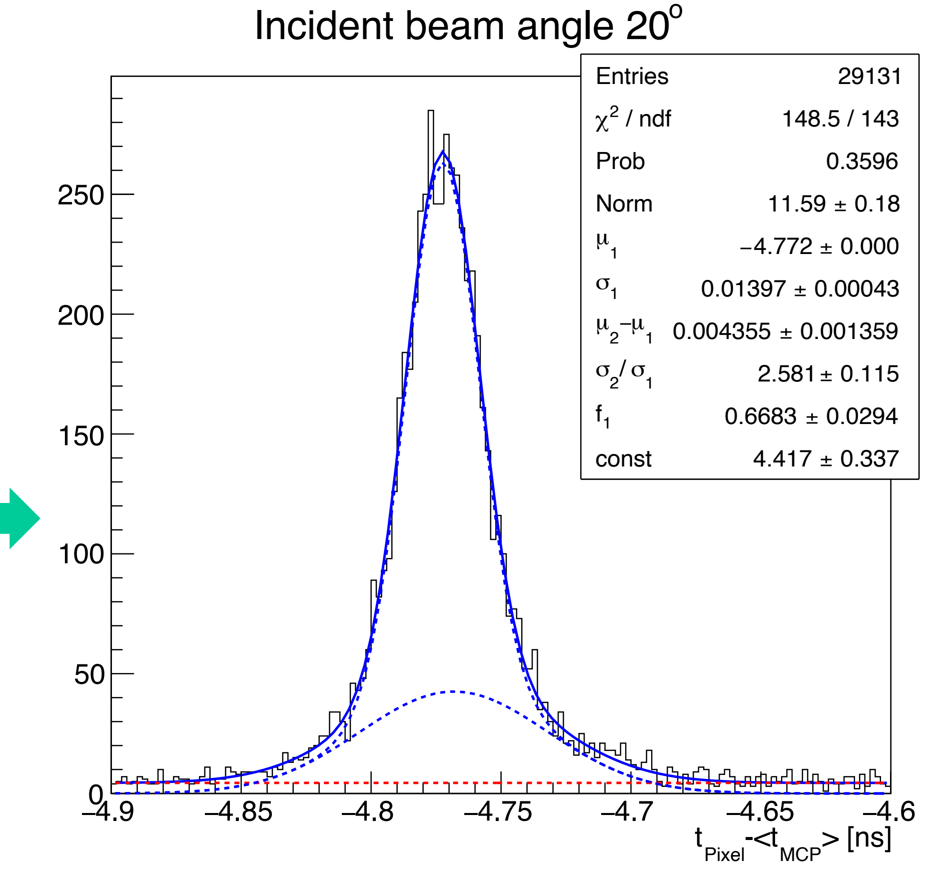
Effect of tilting on distribution shapes

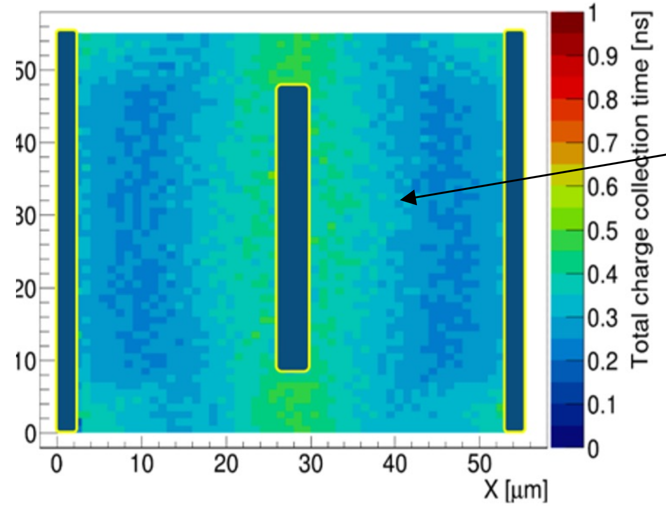
Spline method, SPS/H8 (Nov'21)

Single Pixel @ 50V









Simulated CCT map of a single 3D-trench sensor pixel scan (α_{tilt} = 0°)

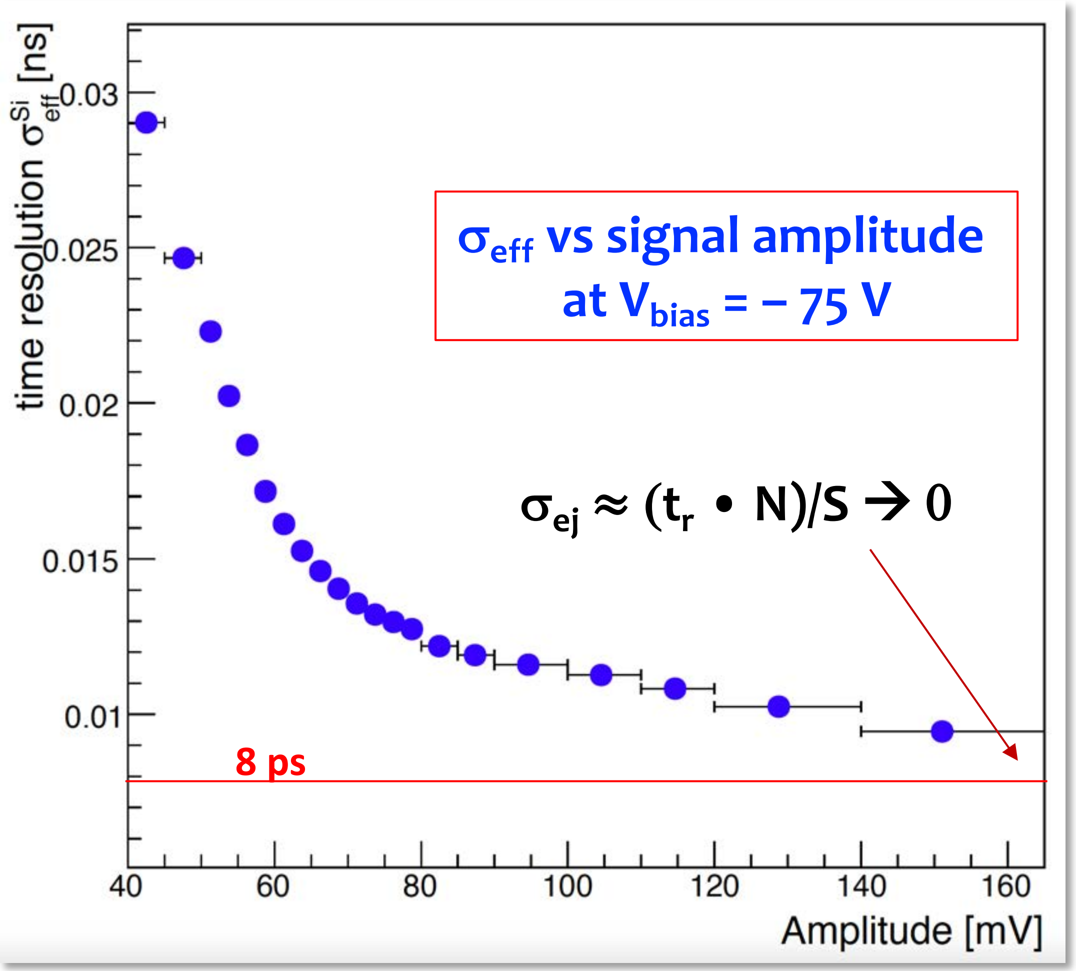
Tilting has the effect of «mixing up» the fast and less-fast regions of the pixels, thus uniforming the timing response

As a result, the shapes are more Gaussian at increasing α_{tilt}

Notice that, due to detection efficiency, α_{tilt} = 20° is the normal working condition of a 3D in a detecting system

Conclusions

1. TimeSPOT 3D-trench pixel sensors show resolutions around 10 ps at fluences ≥ $2.5 \bullet 10^{16}\ n_{eq}/cm^2$, with full efficiency (>99%)
2. Their intrinsic resolution are estimated in the range 8÷9 ps, also corresponding with previous simulations[1]
3. Such performance is measured using high bandwidth, high power FEE
4. The final system performance will be totally dominated by the front-end ASIC[2] and system constraints (power)
5. As of today, 3D-trench pixels appear as the only fully-satisfyng solution when timing at extreme fluences and rates is a mandatory requirement
6. Further tests at higher fluences are planned to find the resistance limit of such pixel sensors
7. Three more production batches are planned (and funded) in 2023-24



The asintote (≈ 9 ps) is an estimate of the intrinsic sensor contribution (when electronic jitter $\sigma_{ej} \rightarrow 0$).
The V_{bias} can almost be increased to ≥ –100 V
At $V_{bias} \approx -100$V, being the measured $\sigma_{ej} = 7$ ps, we can also estimate:

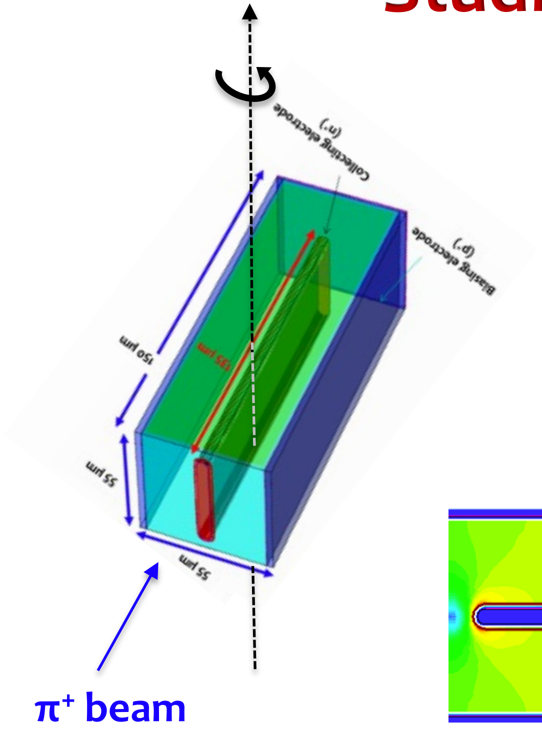
$$\sigma_{t,pixel} \approx \sqrt{[11^2 - 7^2]} \approx 8.5 \text{ ps}$$

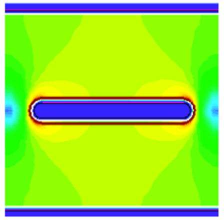
1) Brundu et al. JINST 16 (2021) P09028. doi:10.1088/1748-0221/16/09/p09028
2) See talk #154 on the 14th this week.

INSIGHTS

Studies of Geometric Efficiency: setup

Single pixel, not irradiated

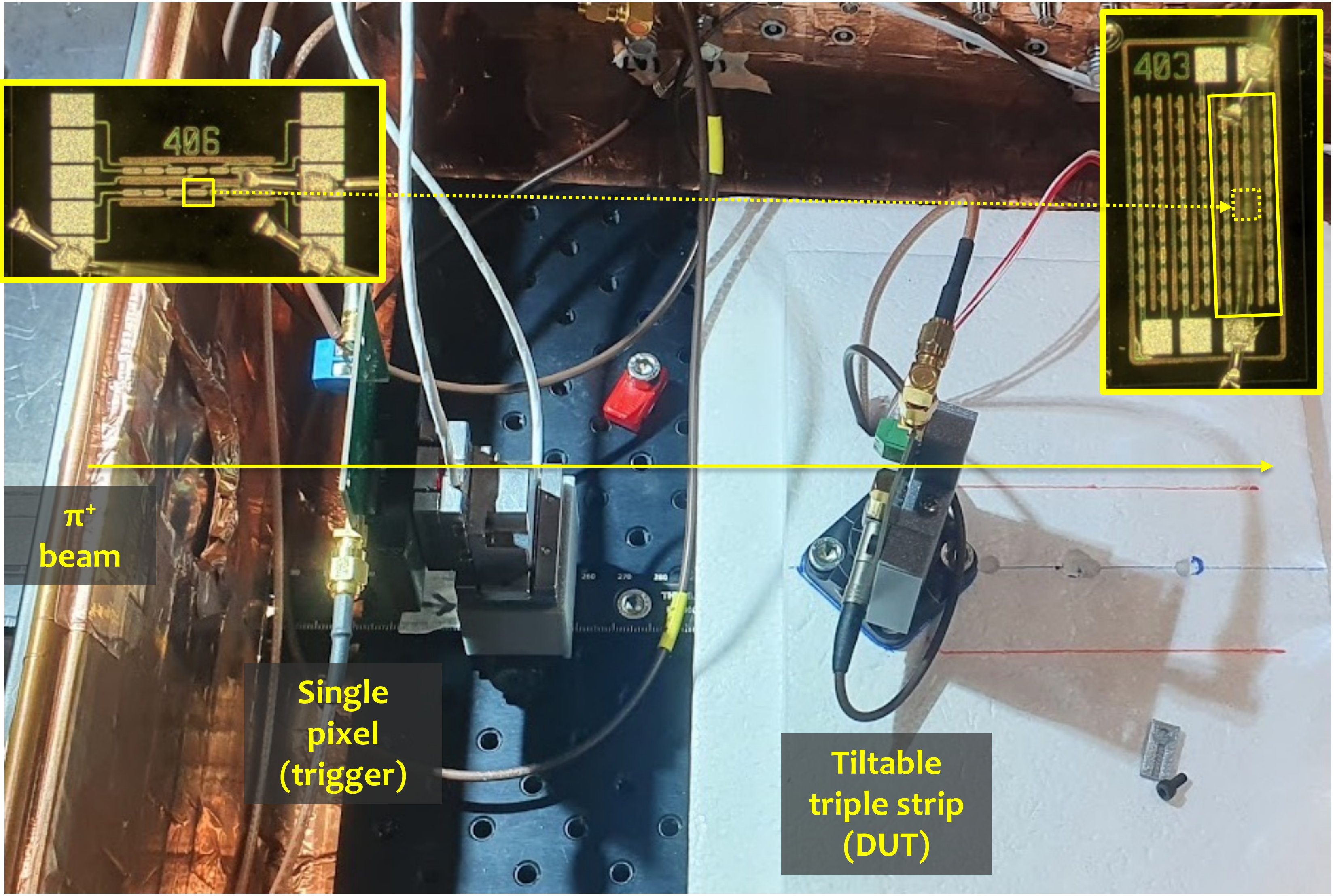




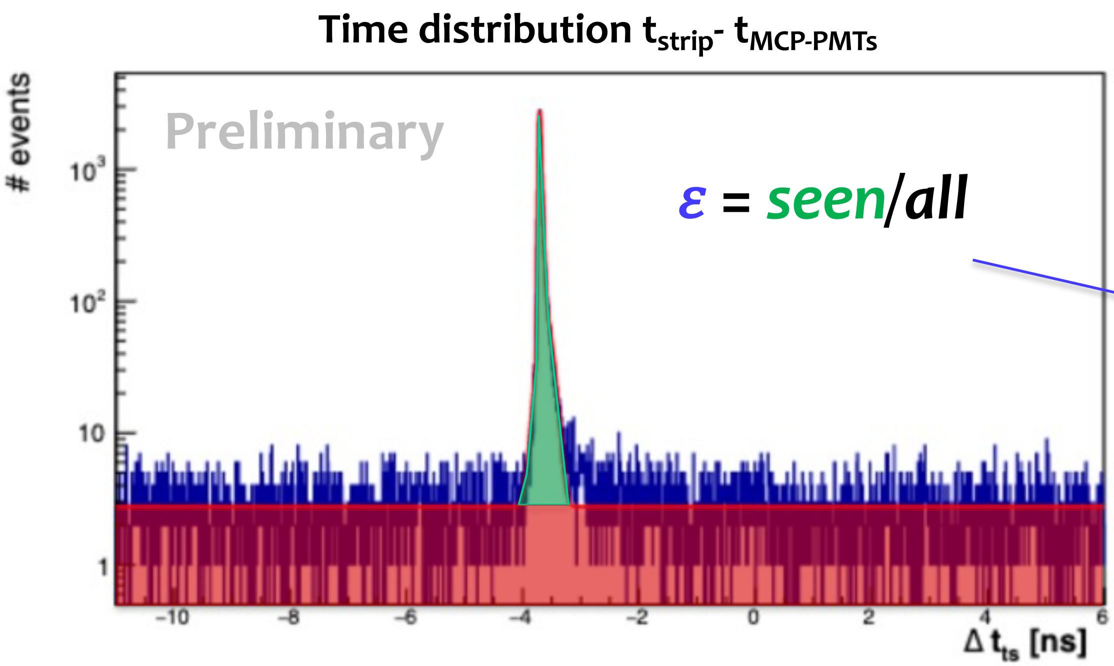
Tilting the sensors with respect to normal incidence should allow **to recover geometric efficiency**

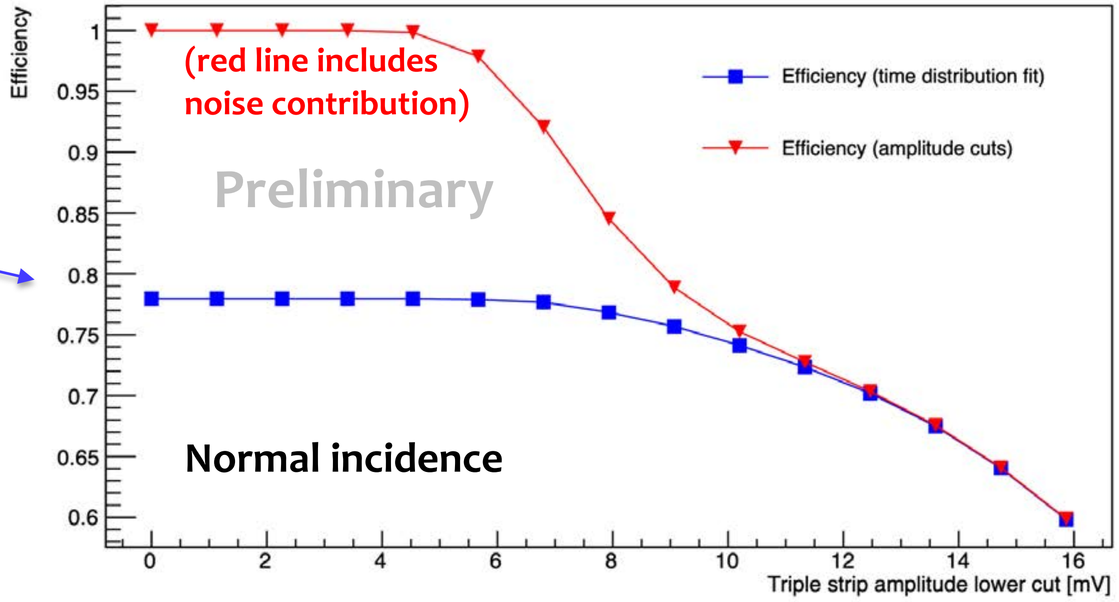
Trigger on one pixel (55 μm x 55 μm, on piezos) centered on a triple strip (165 μm x 550 μm, DUT) and **counting the fraction of signals seen in the triple strip** (on a single FE channel)

The DUT is rotated around the trench direction



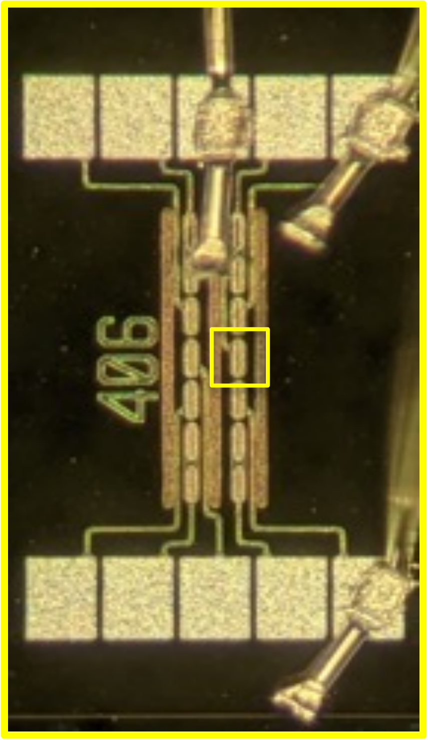
Efficiency: method

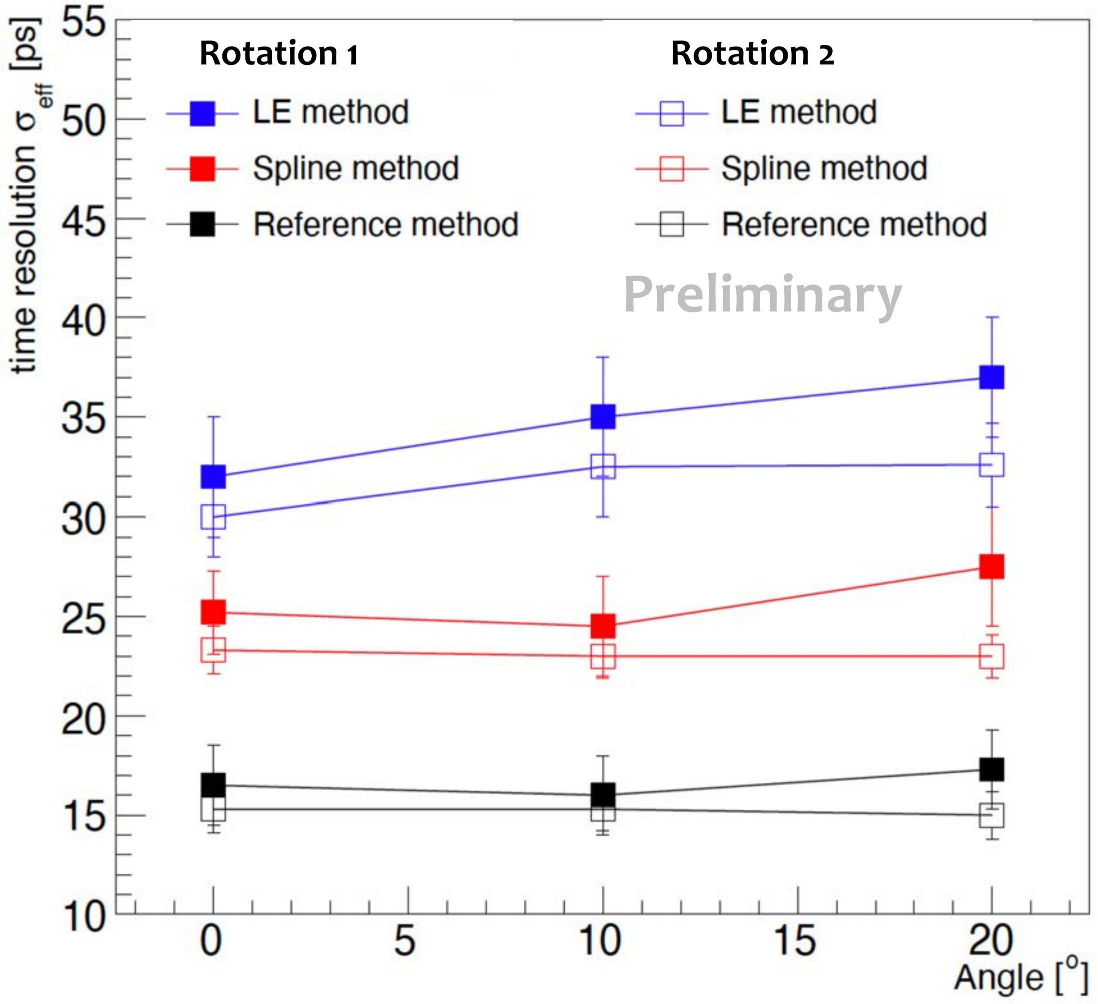


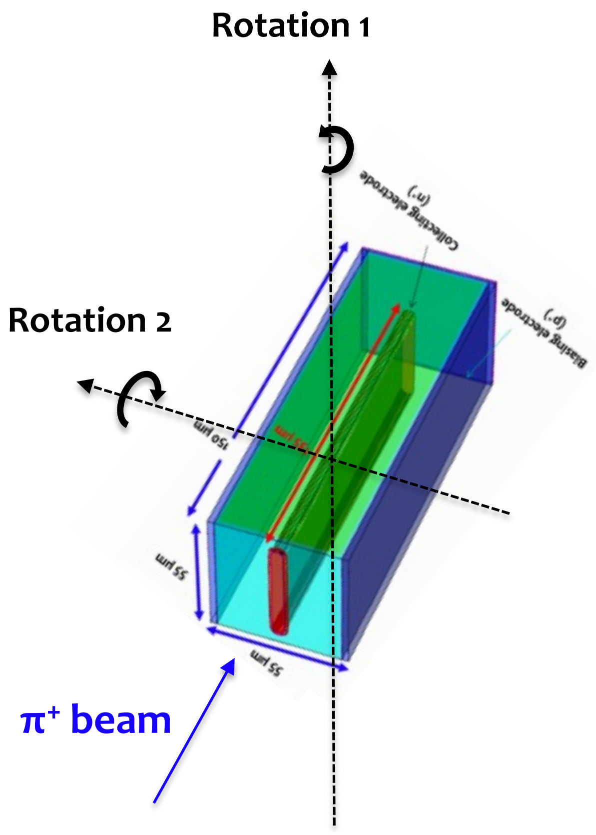


- Time distribution of **all triple-strip signals** w.r.t. MCP-PMTs and count as 'seen' the ones under the peak (the flat background corresponds to undetected hits)
- 3D pixel detection (geometrical) efficiency at normal incidence is in agreement with calculated fraction of active area (~80%)

Tilted sensors: timing performance

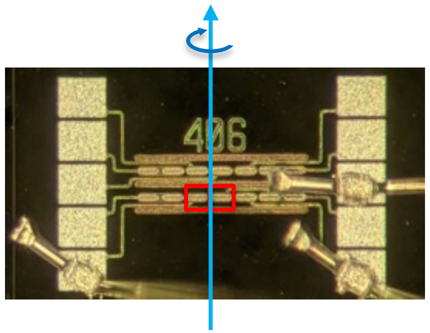






Single Pixel @ 50V

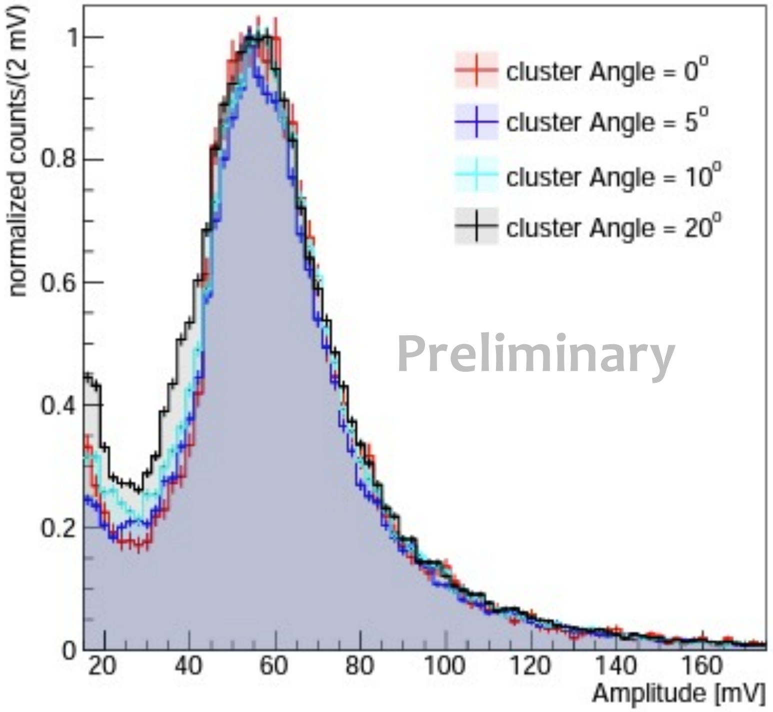
Charge sharing studies: results



When a particle crosses two pixels:

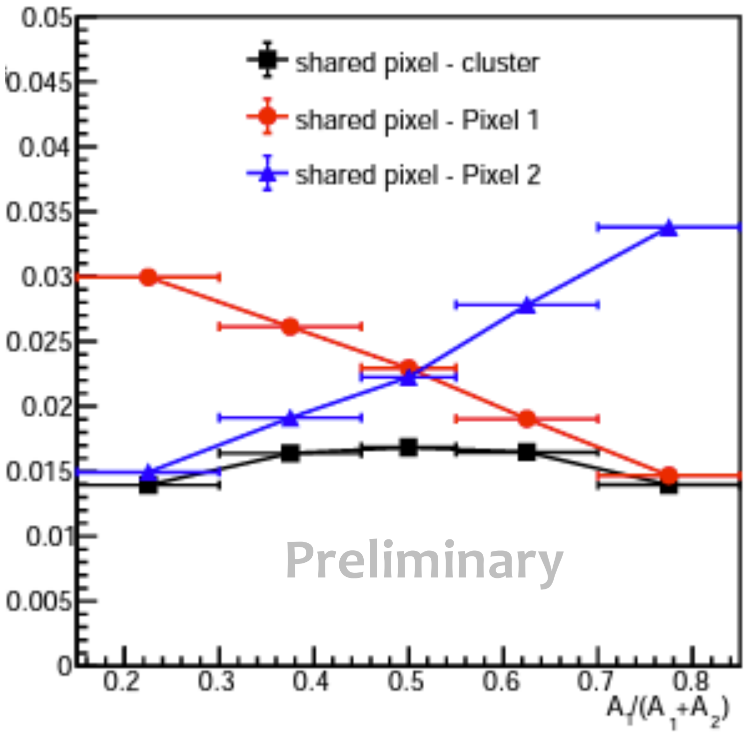
1. Amplitude = sum of the amplitudes of the two signals
2. Time of Arrival = weighted sum on amplitudes of the ToA in the two pixels

Amplitude distributions at different angles



Combining the two pixels information, it is possible to recover the amplitude distribution expected at normal incidence angle

Time resolution as a function of the fraction of sharing



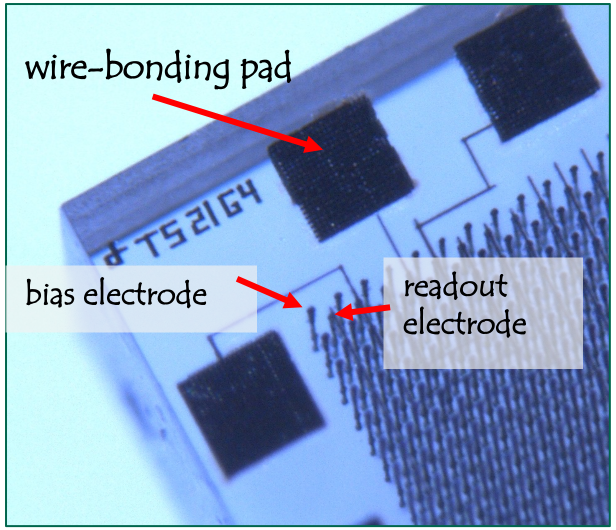
@ tilt angle of 20°

*time resolution from histogram RMS

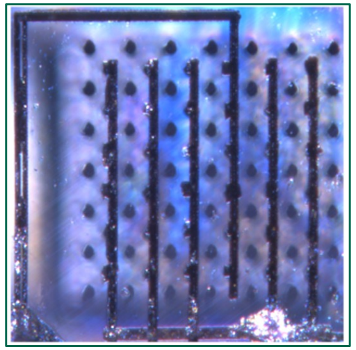
Using the information of both pixels, timing performance improves

Time resolution of 3D-column diamond sensors

By TimeSPOT Firenze group



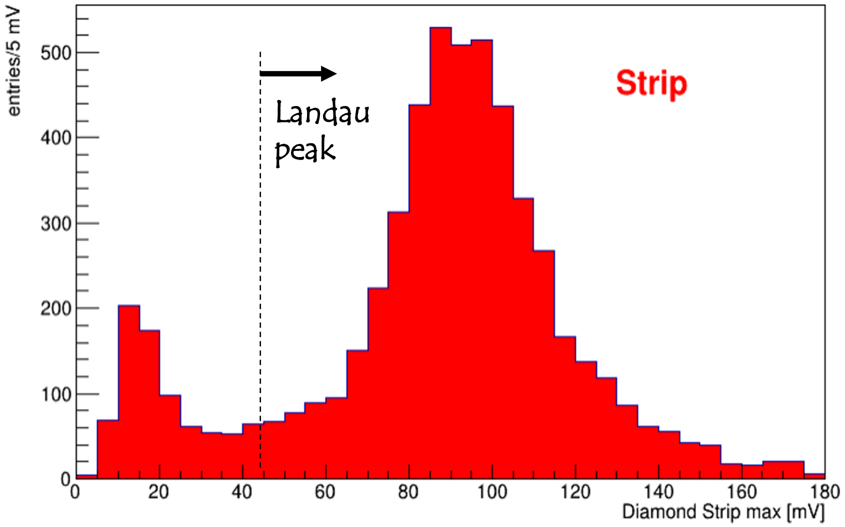
Prototype 32x32 55x55 μm^2 sensor for test-beam

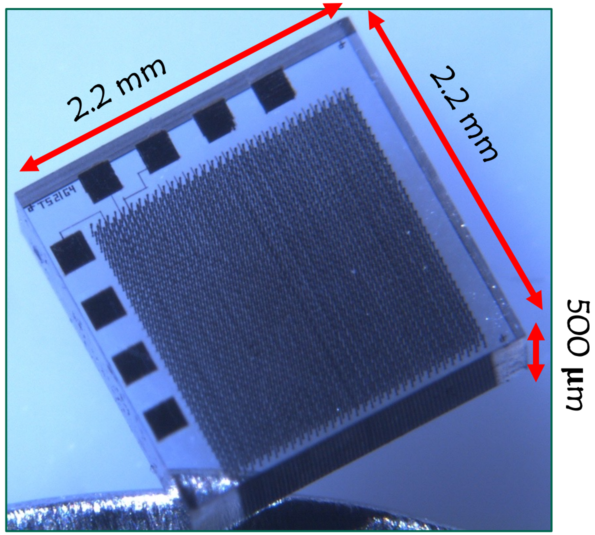


TimeSPOT Silicon pixel or strip used for trigger and scanning of the diamond sensor

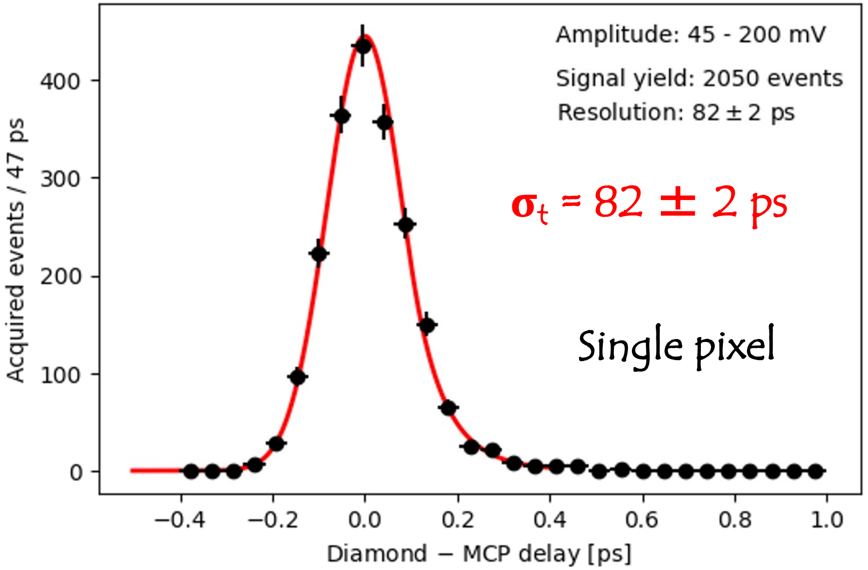
S/N = 18

Single pixel

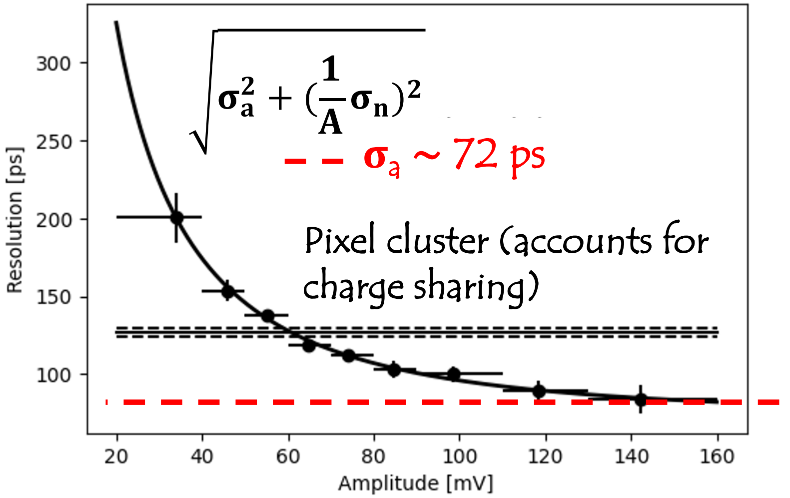




Single crystal CVD diamond by E6



Time resolution



σ_a gives an estimate of the intrinsic sensor resolution